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Crosstalk Effect in Bundled SWCNT, DWCNT and MWCNT Carbon Nanotubes

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Abstract: In this paper, different models of parallel Carbon nanotube Bundles are carried out and simulated. In the first place, a model of three parallel SWCNT (singe walled carbon nanotube) Bundles and DWCNT (double walled carbon nanotube) Bundles was established and simulated. It has been noticed that the variation on the number of Carbon nanotubes in the bundle has an impact on the crosstalk amplitude. In the second place, a model of three parallel MWCNT (multi walled carbon nanotube) Bundles was established and simulated and the crosstalk effect has been noticed and compared with SWCNT/DWCNT Bundles. Finally a model of mixed Bundles (Single-Double-Single) and (Double-Single-Double) was carried out and simulated. All simulations were established using Pspice.

Key words: SWCNT, DWCNT, MWCNT, SWCNT Bundle, DWCNT Bundle, MWCNT Bundle, crosstalk.

1. Introduction

Throughout the past history of embedded systems, interconnects did not get so much attention as far as the reliability of the integrated circuits was concerned, but due to the continuous process of miniaturization, the feature size reduced and the interconnect delay became more important, the thing that made the performance of ICs (integrated circuits) determined by the current-carrying capacity and parasitic resistance, inductance and capacitance of these interconnects. Nowadays, interconnects in general play an important role in determining the performance of high speed ICs. The miniaturization of devices demands longer and much faster interconnects with very lower consumption of power, that's why new conductive materials with high performance are necessary for interconnect development in the next generation of integrated circuits.

After their discovery, CNTs (carbon nanotubes) can be considered as one of the most emerging materials in the field of microelectronics and a potential alternative to actual copper interconnect lines. Various researches have been carried out in order to predict and enumerate the properties of CNTs. The majority of these researches predicted CNTs to have high thermal stability, huge current carrying capability, mechanical strength and a long mean free path as compared to traditional copper wires (Cu).

Physically speaking, CNTs are sheets of graphene rolled up as cylinders and they can be categorized as: SWCNT (singe walled carbon nanotube), with only one shell and a diameter ranging from 0.4 to 4 nm, SWCNT can be either metallic or semi-conducting depending on its chirality. MWCNT (multi walled carbon nanotube), with many concentric shells and a diameter ranging from several nanometers to tens of nanometers, is always metallic. DWCNT (double walled carbon nanotube) is a special case of MWCNT with only two concentric shells. CNTs are generally used in bundles and not in a single form.

Interconnect lines performance, regardless of the type of material used, is brutally affected by the

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phenomena of crosstalk due to several causes in VLSI designs. Crosstalk is an unexpected noise interference generated because of electromagnetic coupling between two or several neighboring transmission lines. The crosstalk in interconnect lines may cause time delay and the appearance of a logical error in the output of an interconnection which is not supposed to carry any signal.

In this paper, we present and simulate different models of bundled SWCNT, DWCNT and MWCNT in different architectures (uniform and mixed), the rest of this paper is organized as follows: in the first section, a crosstalk analysis in SWCNT Bundles has been carried out using an ESC (equivalent single conductor) of SWCNT Bundle. The same thing has been done for DWCNT and MWCNT in sections 2 and 3 respectively. In section 4 a model of mixed CNT Bundles is presented and simulated. The last section is dedicated for results and discussion.

2. Crosstalk Effect in SWCNT Bundles

The model and the geometry used to analyze and simulate the crosstalk in SWCNT Bundles are shown in Fig. 1. The same model and geometry are used for DWCNT, MWCNT and Cu wires.

A normal geometry of a SWCNT Bundle contains several SWCNT gathered in parallel with a spacing sp between each two neighboring CNT, H and W are the height and the width of the Bundle respectively and D is the diameter of each SWCNT.

The equivalent circuit model of a SWCNT (Fig. 2a) was proposed in many researches [2-5], with the quantum resistance R_{Qua} at each end of the interconnect, and it is given by $h/4e^2N \approx 12.9k\Omega$, h is Planck's constant, e is the charge of an electron and N is the number of conducting channels (basically equal to 2 for an individual SWCNT). R_{Con} is the imperfect contact resistance (20-120 kΩ), which depends on the process of fabrication. As shown in Fig. 2a, the distributed parameters, namely scattering resistance R_{Sca}, kinetic L_{Kin} and magnetic L_{Mag} inductance, quantum capacitance C_{Qua} and electrostatic capacitance C_{Ele} are given in Ref. [1].

Based on the model of individual SWCNT, the ESC's parameter of SWCNT bundle was extracted as:

- The total resistance of the SWCNT Bundle is given by:

$$R_{Bundle} = (R_{Con} + R_{Qua} + R_{Sca} l_{CNT}) / N_{CNT} \quad (1)$$

where L_{CNT} is the number of carbon nanotubes in the Bundle.

- SWCNT Bundle's total inductance is given by:

$$L_{Bundle} = L_{CNT} / N_{CNT} \quad (2)$$

where L_{CNT} the inductance of the nanotube, and it is given by:

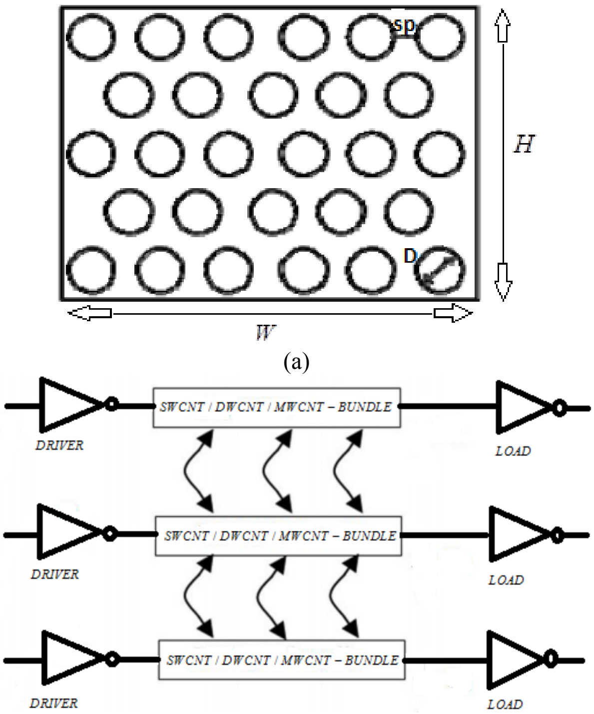
$$L_{CNT} = L_{Kin} + L_{Mag} \quad (3)$$

- The total quantum capacitance of the SWCNT Bundle is given by:

$$C_{Qua-Bundle} = C_{Qua} N_{CNT} \quad (4)$$

- The electrostatic capacitance between a SWCNT Bundle and the ground, and the one between two SWCNT Bundles are given respectively by:

$$C_{Bundle-Bundle} = (\pi\varepsilon) / \cosh^{-1}(sp / D) \quad (5)$$



(a)

(b)

Fig. 1 (a) Geometry of a SWCNT Bundle. (b) Model of three neighboring (Single/Double/Multi) CNT Bundles.

$$C_{Bundle-Ground} = (2\pi\varepsilon) / \ln(H / D) \quad (6)$$

This ESC model of SWCNT Bundle was simulated in Pspice using three neighboring Bundles in parallel as shown in Fig. 1b, the Bundle in the middle is considered as Victim (no signal is spreading on it), meanwhile the two other Bundles are set to be aggressors (they are carrying a step signal). The results of the simulation are discussed and compared to Cu wires in the results section.

3. Crosstalk Effect in DWCNT Bundles

DWCNT is the simplest geometry of an MWCNT; it is two concentric grapheme shells with a space of 0.34 nm between them both. Since the diameter of the external shell is different from that of the internal one in a DWCNT, we will have as a result two per-unit-length resistances denoted by R_E and R_I respectively. We need to consider another parameter which is the conductance between two shells $G = (10K\Omega)^{-1} / \mu m$, it is due to tunneling effect between the two shells of the DWCNT. As a consequence, the resistances of a DWCNT Bundle are calculated by:

$$R_{IB} = (R_{Con} + R_{Qua-I} + R_{Sca-I} l_{CNT}) / N_{CNT} \quad (7)$$

$$R_{EB} = (R_{Con} + R_{Qua-E} + R_{Sca-E} l_{CNT}) / N_{CNT} \quad (8)$$

$$G_B = G N_{CNT} \quad (9)$$

Since DWCNT behaves as a metallic interconnect, the electrostatic capacitance between the two neighboring shells is expressed by:

$$C_E = 2\pi\varepsilon / \ln(D_{ex} / D_{in}) \quad (10)$$

The per-unit-length quantum capacitance of the DWCNT Bundle is calculated by:

$$C_{Qua-Bundle} = C_{Qua} N_{CNT} \quad (11)$$

Due to the independence of the per-unit-length inductance of a DWCNT Bundle from the variation of the diameter, its value will be considered as the same as that of SWCNT Bundle. Based on these parameters, a model of three neighboring DWCNT Bundles, similar to the model shown in Fig. 1b, is built and simulated in Pspice. The results are discussed in the results section.

4. Crosstalk Effect in MWCNT Bundles

MWCNT interconnect is one of the easiest nanotube interconnect to be fabricated, and it is always metallic. It contains several concentric graphene sheets rolled up with a spacing of 0.34 nm which is the Van Der Waal's gap. The equivalent circuit model of an individual MWCNT is shown in Fig. 2b.

The capacitance, the inductance and the resistance of each shell depend on the number of shells; the number of shells of a MWCNT is related to the diameter by the equation:

$$N_{shell}(D) = aD + b \quad (12)$$

where D is the diameter, a = 0.0612 nm^{-1} and b = 0.425.

The resistance, inductance and capacitance of each shell of a MWCNT interconnect are given respectively by:

$$R_{shell} = (R_{Qua} + R_{Sca} / \lambda_{CNT}) / N_{shell} \quad (13)$$

$$L_{Kin/shell} = L_{Kin} / N_{shell} \quad (14)$$

$$C_{Qua/shell} = C_{Qua} N_{shell} \quad (15)$$

To have an idea about the phenomena of crosstalk in MWCNT Bundle, we consider the numerical parameters of the model described in Refs. [5, 6].

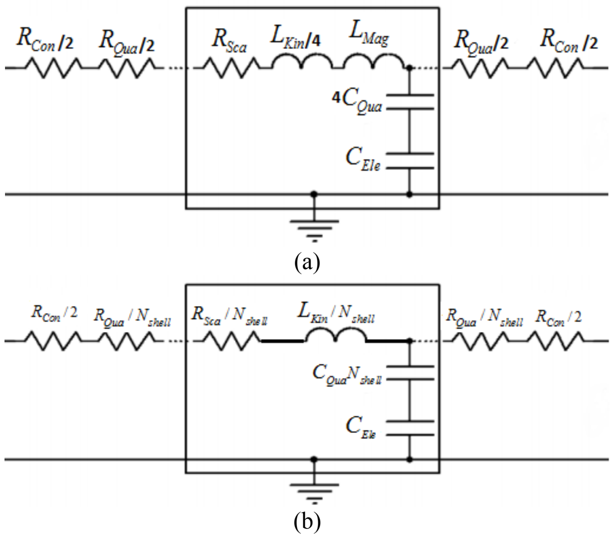


Fig. 2 (a) Equivalent circuit of an individual SWCNT interconnect, (b) Equivalent circuit of an individual MWCNT interconnect.

In all the simulations that we carried out, the aggressor are excited by a voltage of 1V with rise time of 0.1 ns, the internal resistance and capacitance of the generator are respectively R = 2 kΩ and C = 0.1 pF, the interconnect length is 1 μm.

5. Results and Discussion

To notice the effect of crosstalk in the different types of bundled Carbon nanotubes we simulate the model in Fig. 1b using SWCNT, DWCNT, MWCNT and a mixed structure of two SWCNT Bundles, and one DWCNT Bundle in a first time, and then two DWCNT Bundles with one SWCNT Bundle in a second time. We simulate all those cases using different numbers of carbon nanotubes in the Bundle (25, 35 and 45). The aggressor Bundles are excited by a voltage of 1 V (Step Signal) with a rise time of 0.1 ns, the internal resistance and capacitance of the generator are respectively $R = 2K\Omega$ and $C = 0.1pF$. The interconnect length is 1 μm.

Fig. 3 shows the amplitude of crosstalk in the victim SWCNT Bundle, as far as the number of carbon nanotubes increases in the bundle the agressivity of the crosstalk becomes more important, it reached almost 700 μV for 45 Carbon nanotubes in the bundle. In Fig. 4, we can see the same thing happen with DWCNT Bundles using the same numbers of carbon nanotubes, but the crosstalk amplitude is less important than in SWCNT Bundle, that is why DWCNT is more efficient in local interconnects in embedded systems.

The last simulation is the mixed bundled carbon nanotubes. Fig. 5a is the crosstalk effect in a SWCNT Bundle (victim) surrounded by two DWCNT Bundles (Aggressors) using different numbers of Carbon nanotubes. The crosstalk amplitude reached almost 290 μv for 45 carbon nanotube. Fig. 5b shows the crosstalk effect in a DWCNT Bundle with two neighboring SWCNT Bundles, the crosstalk is very aggressive in comparison with the other models; it reached almost 0.8 mv for 45 carbon nanotubes in the bundle.

After all, all the crosstalk amplitudes in the different models of Bundled Carbon nanotubes are still

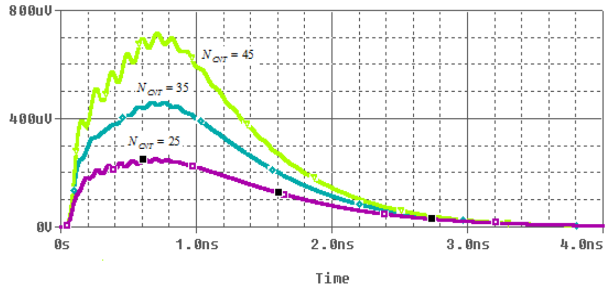


Fig. 3 Crosstalk effect in victim SWCNT Bundle neighbored by two SWCNT Bundles with different number of Carbon nanotubes.

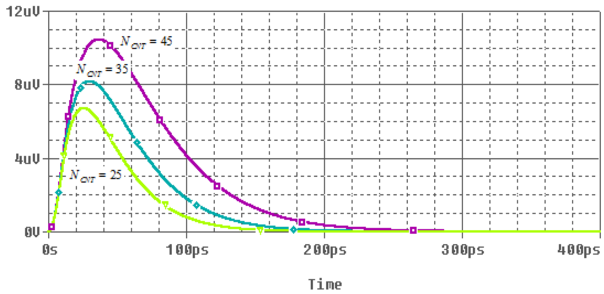


Fig. 4 Crosstalk effect in victim DWCNT Bundle neighbored by two DWCNT Bundles with different number of carbon nanotubes.

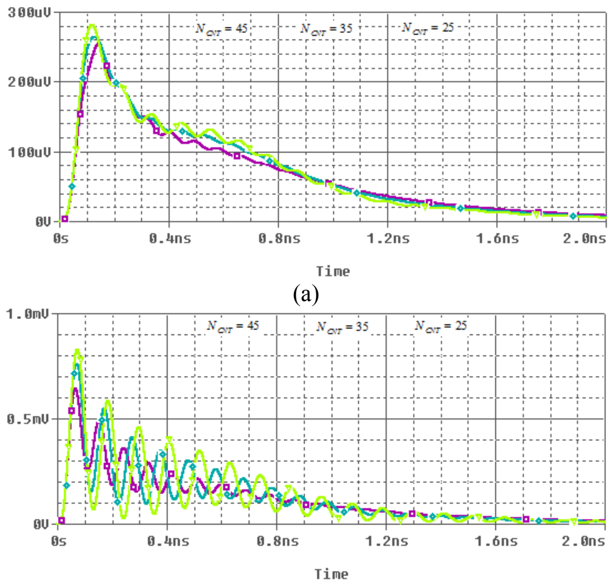


Fig. 5 (a) Crosstalk effect in victim DWCNT Bundle neighbored by two SWCNT Bundles with different number of Carbon nanotubes. (b) Crosstalk effect in victim SWCNT Bundle neighbored by two DWCNT Bundles with different number of Carbon nanotubes.

much lower than the Crosstalk in Cu wires in VLSI nanoscale interconnects according to the literature, which is why carbon nanotube materials, are very promising to substitute the Cu wires in nanoscale electronic systems.

6. Conclusions

In this paper, crosstalk in uniform and mixed Bundled was examined. It is shown that as far as the number of Carbon nanotubes increases in the bundle, the crosstalk effect on the victim Bundle becomes more important, the worst result was the SWCNT surrounded by two DWCNT. All the models simulated in this work showed that Bundled Carbon nanotube interconnects can outperform the Cu wires in VLSI interconnect systems.

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